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Possible influence of quark-gluon plasma formation on lateral distributions of charged particles and muons in EAS

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Lateral distributions of extensive air shower (EAS) charged particles and muons obtained with the Yakutsk array change considerably at energies above $3 \cdot 10^{18}$ eV. At the same time calculations based on modern quark-gluon string models demonstrate no such effects. In this paper we discuss whether quark-gluon plasma formation at superhigh energies could produce influence on EAS characteristics in question and explore specially showers generated by heavy nuclei.

1. Introduction

According to the Yakutsk array experimental data [1] the lateral structure of EAS exhibits essential changes at energies above $3 \cdot 10^{18}$ eV when compared with data at lower energies. Such data may indicate that some new physics occurs after passing the threshold mentioned. Our previous calculations [1] performed in the framework of QGSJET model [2] did not show any appreciable changes of EAS lateral distribution functions (LDF). The same result was obtained in [3], where the hadronic interaction model NEXUS [4] was used. These results appear quite natural as the models used in the analysis demonstrate no drastic changes of hadronic interaction characteristics. Now the physical community is expecting that the Large Hadron collider (LHC) should give us ultimate evidence in favour of the quark-gluon plasma (QGP) existence and so it seems natural to discuss whether the QGP formation could produce any noticeable effects in EAS characteristics. Evidently, first of all the QGP formation should manifest in the collisions of Fe nuclei. In our analysis we use the results obtained with the QGSJET model and predictions of the model HYDRO [5] (see also [6]) that exploits the ideas of the hydrodynamic model and offers a natural and relatively simple explanation for the observed growth of the mean transverse momentum with increasing mass in most central nuclear collisions at SPS and RHIC.

2. Results of calculations

In our calculations we used the hybrid scheme described in [7 and 3]. Figures 1-3 present results of the charged particle LDF analysis. It follows from the Figure 1 that there is no significant difference (exceeding 5%) when one compares $\rho_{600}(E_0)$ dependence for Fe and p primaries. As may be seen from the Figure 2 the value of the power index $\alpha_\rho(R)$ in the relation $\rho(R) \sim E_0^{\alpha_\rho(R)}$ in close to 1 irrespectively of the mass number A, whereas at distances <600 m and >600 m $\alpha_\rho(R)$ differs from 1 and some dependence on A is observed. The values of $\alpha_\rho(R)$ were inferred for the energy interval 10^{17}–10^{18} eV.

Due to this difference the value of $\rho_R^{(Fe)}(E_0)/\rho_R^{(p)}(E_0)$ changes slowly with R from 0.65 at $R = 100$ m to 1.10 at R =1000 m (the values of the ratio are given for $E_0 = 3 \cdot 10^{17}$ eV). On the contrary, the ratio of muon densities in the same distance range is always greater than 1 and rises slowly from 1.28 at $R = 100$ m to 1.66 at $R = 1000$ m (see Figure 3)

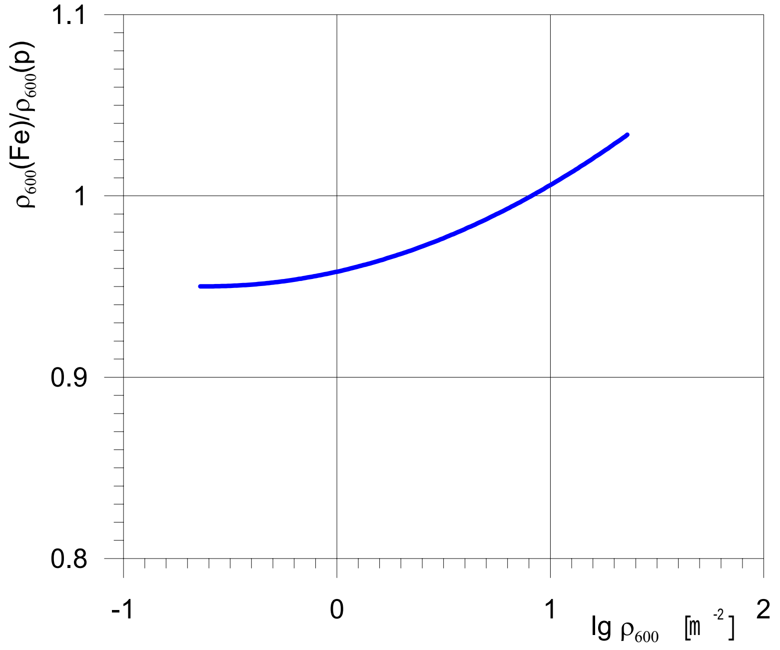

Figure 1 The ratio of charged particle densities in Fe and p initiated EAS at fixed primary energy in the framework of the QGSJET model.

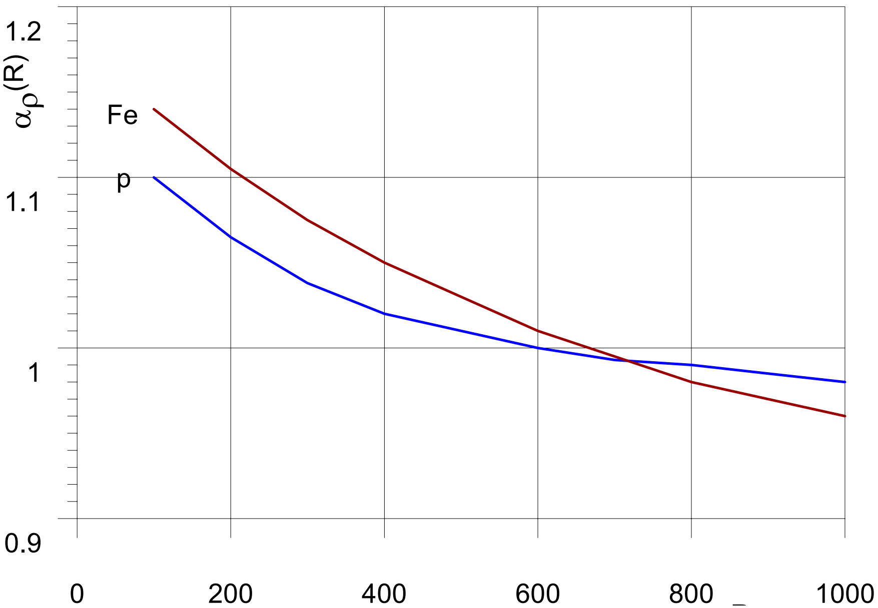

Figure 2 The dependence of $\alpha_\rho(R)$ for p and Fe primaries (QGSJET model)

3. Discussion

So EAS spatial characteristics calculated in the framework of the QGSJET model (as well as in the framework of any Gribov-Redge model) demonstrate a smooth behavior and there is no sense in our waiting for an abrupt change of the LDF parameters with primary energy. What can be expected if one assumes that

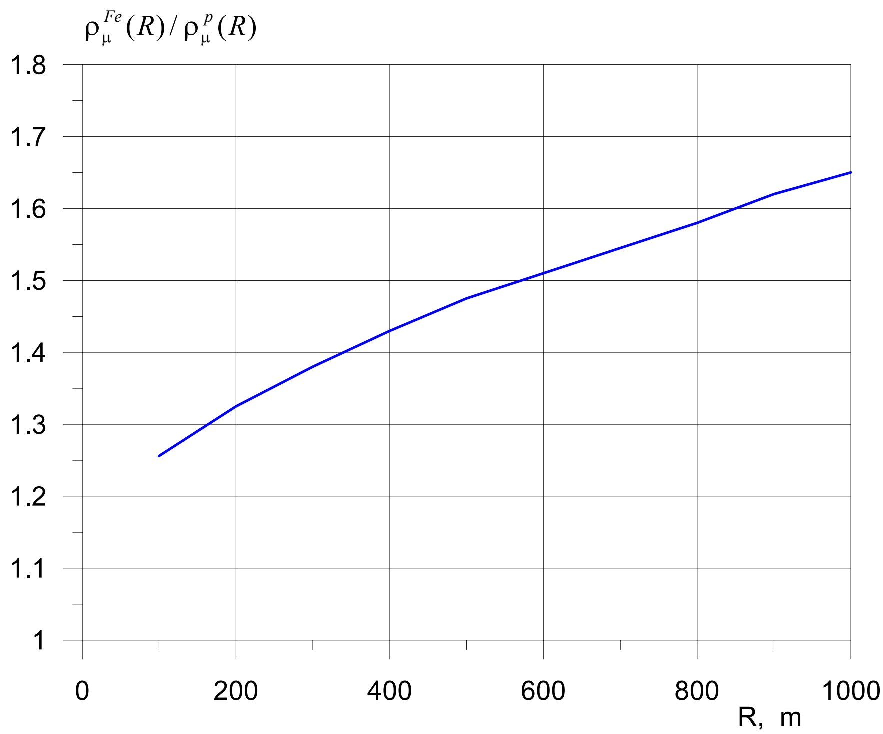

Figure 3 The ratio of muon densities in Fe and p initiated showers for different R (QGSJET model, $E_\mu \geq 1$ GeV)

at some energy (approximately corresponding to $\sqrt{s_{NN}} \approx 5.5$ TeV) the formation of the QGP begins? We would like to outline, that there exists a pronounced difference between predictions of the very first papers where the formation of the QGP was assumed (see, for example [8]) and contemporary ones [5,6]. The assumptions of [8] were analyzed in [9] and it was shown that essential changes of EAS characteristics were to be expected only at sufficiently high energies of the secondary particles (above 100 GeV for muons).The total number of low energy muons obtained in [9] did not differ much from usual predictions. Also we should take into account that from the contemporary standpoint, the changes of the elementary interaction characteristics are essentially less than it was supposed in the very beginning. For example, according [6] the average hadron's transverse momentum at estimated "freeze-out" (see [5,6]) temperature $T_f = 140$ MeV is estimated as $< P_T^h >= 0.55$ GeV/c and following particle ratios are expected $\pi^\pm : k^\pm : p^\pm = 24:6:1$, $\pi^\pm : \pi^0 = 2:1$, $k^\pm : k^0 = 1:1$, $p:n = 1:1$. These values do not differ much from what can be expected in the framework of models neglecting the QGP formation. Besides one should not forget that the influence of

P_T connected to the parents of the particle in question is much less than the influence of P_T of the particle itself. Therefore one may conclude that such an enlargement of the parent's P_T is not sufficient to produce a desirable effect on the EAS spatial distributions even if we consider all the collisions produced by Fe nuclei as the central ones.

But such an assumption is not adequate. Indeed, after averaging over the impact parameter one may easily obtain that in iron-nitrogen collisions the number of interacting nucleons from Fe nuclei is essentially less than 1/2 of the total nucleon number (see [9]). This also prevents serious changes of LDFs.

It is possible to obtain higher values of $< P_T^h >$ if one accept the temperature of "freezing out" about 1 GeV or even greater. But even in such a case it would be difficult to expect significant changes of LDFs calculated for low threshold.

4. Acknowledgements

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